Public

Advances in Predictive Plasma Formation Modeling

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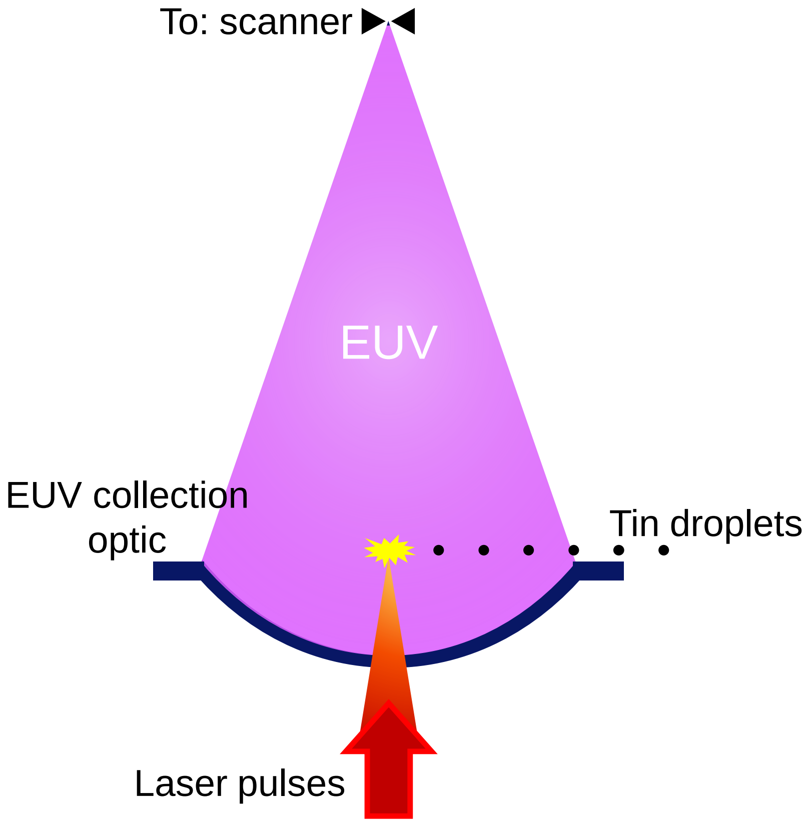
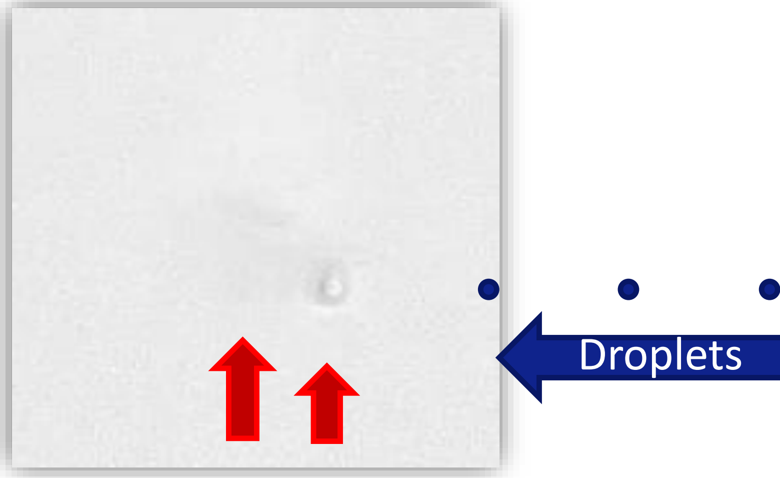
2016 International Workshop on EUV and Soft X-Ray Sources

LLNL-PRES-682277
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Introduction to a laser produced plasma EUV light source



Movie: Backlight shadowgrams from a 3300 MOPA+PP source



MOPA+PP:

Pre-pulse laser

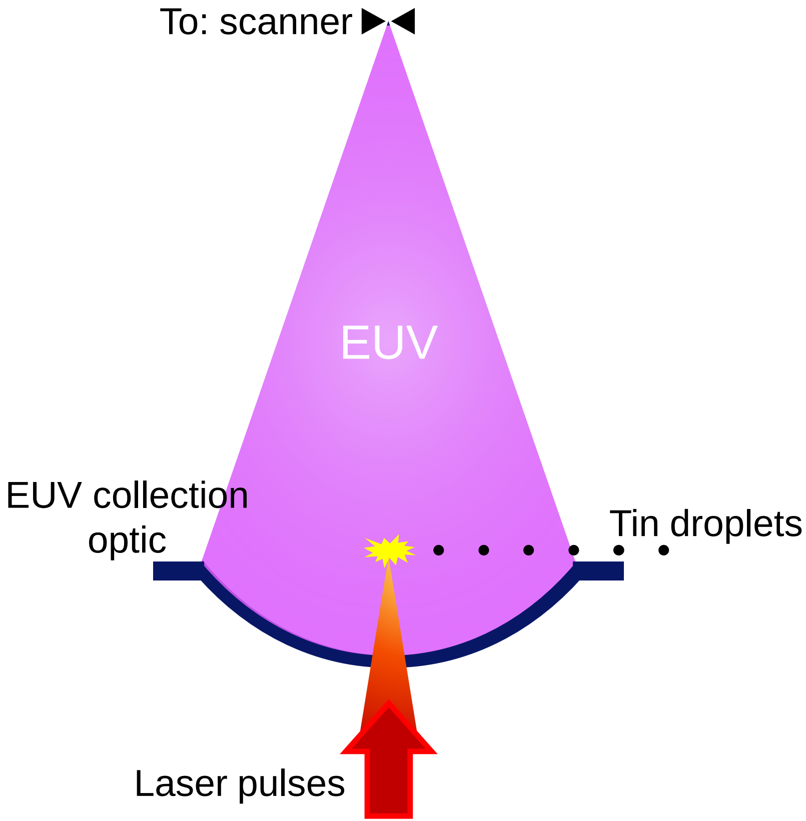
→Expands the droplet and prepares the Sn target

Main-pulse laser

→Heats and ionizes the Sn target to produce EUV light

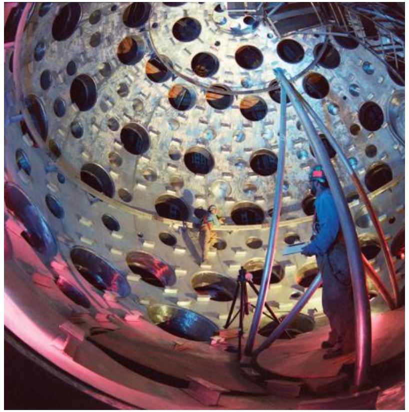
Why do we pursue plasma modeling?

Motivation: To maximize efficiency of laser to EUV power conversion



- Increase the rate of learning and test current roadmap assumptions
- Scan parameters that are experimentally inaccessible
- Deepen understanding and intuition to enable better experimental designs

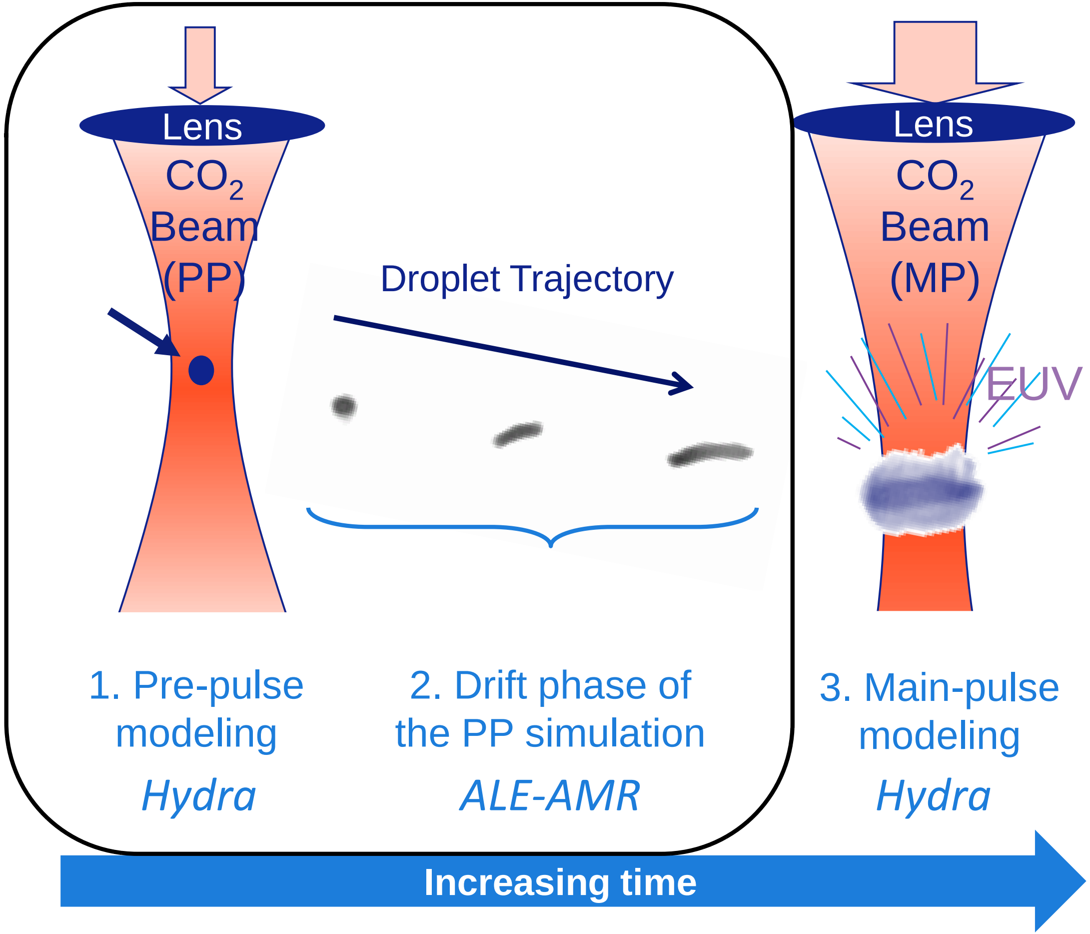
Collaborating with Lawrence Livermore National Lab



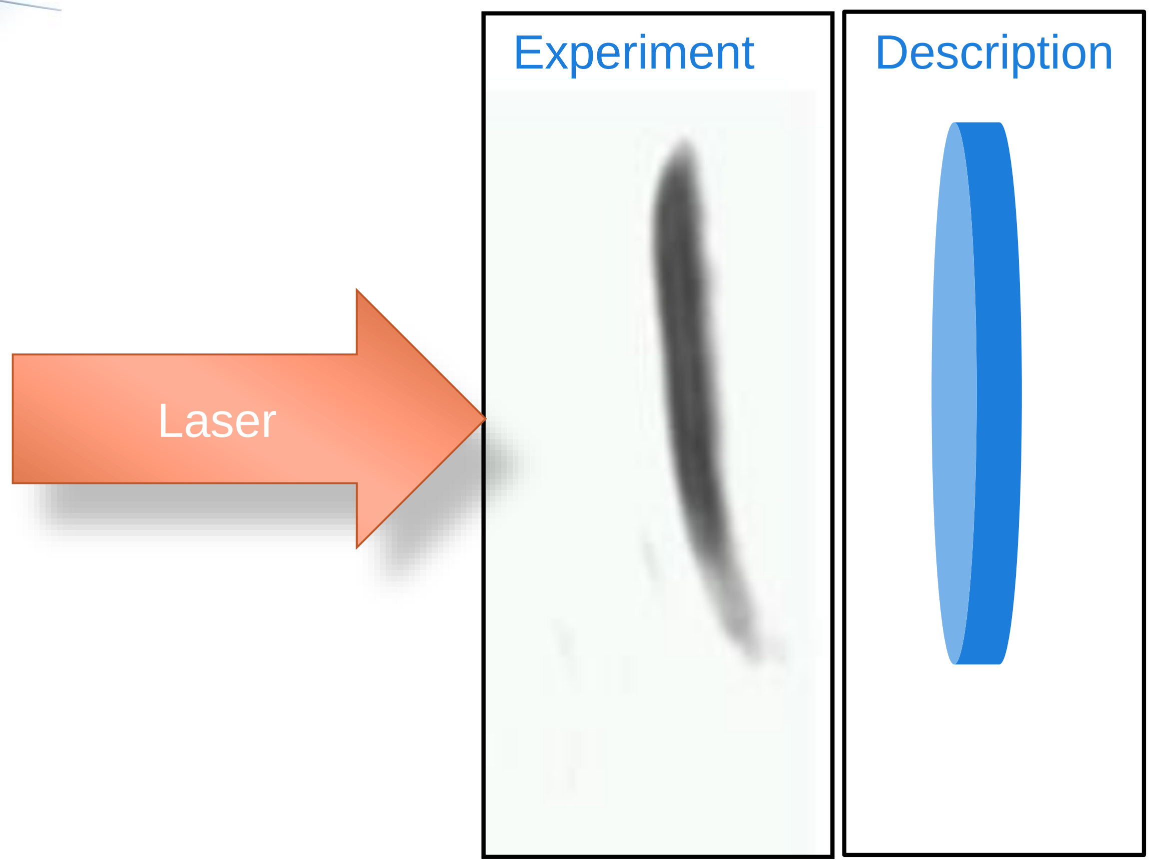
Sequoia: at LLNL, BlueGene/Q architecture

- LLNL is a United States government research facility chartered with the development of technologies in the areas of bio-security, counter terrorism, defense, intelligence, weapons, and energy generation.
- Powerful computational resources and world-class scientists
    - One of the fastest computers in the world is available with 1.6 million cores
- LLNL has a 3D plasma simulations code and therefore can simulate the *real* problem since our plasma is fundamentally 3D (tilts, anisotropies, etc.).
    - Highly complex code under development for over 20 years
    - Ability to model a pulsed laser plasma source
    - LLNL has capability to run “full” problem from laser pre-pulse through the main-pulse interaction

The full problem was broken up into 3 simulation efforts



Reminder: The typical way we have described targets

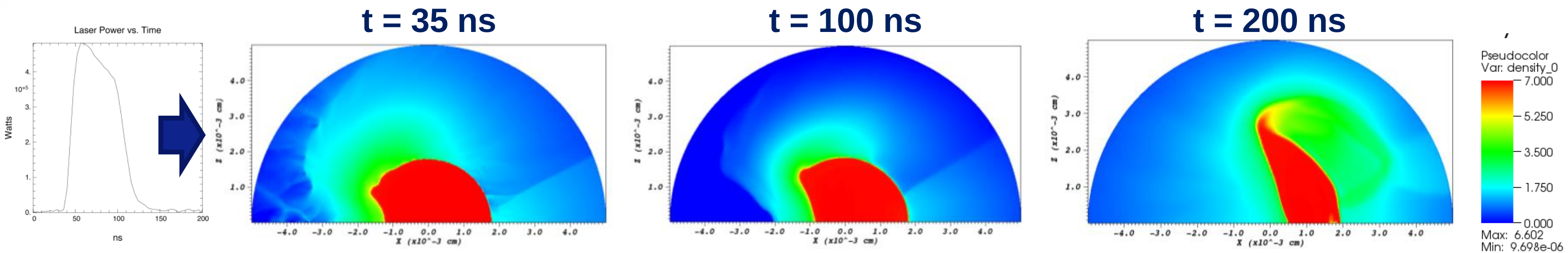


The standard assumption used to describe expanded Tin targets is a flat disk that conserves the mass of a droplet

- The diameter of the disk is chosen to match the diameter of our shadowgrams.
- The thickness of the disk is chosen to match the droplets initial volume.

What simulation capabilities have we developed?

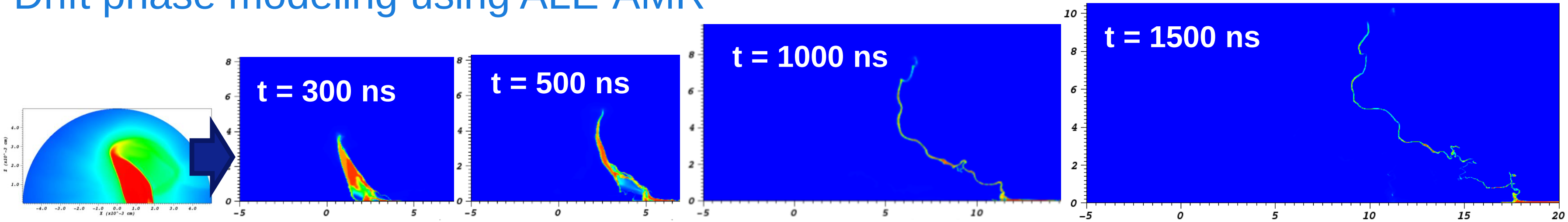
Pre-pulse modeling



Input

A small plasma forms at the front side of the droplet that initiates the forces and subsequent shock waves that drive the expansion process.

Drift phase modeling using ALE-AMR

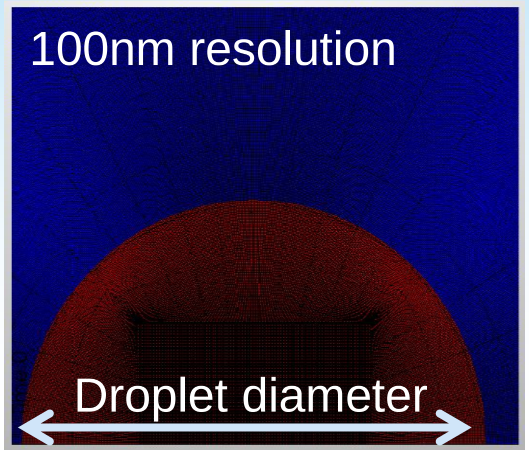


Input

An adaptive mesh tracks the expanding droplet material for more than 2us.

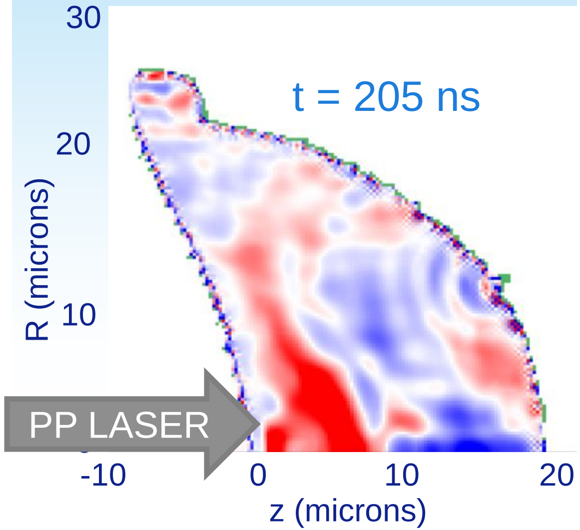
Discovering the physics critical to pre-pulse simulation accuracy

1. High resolution intelligent mesh that adapts resolution where needed.



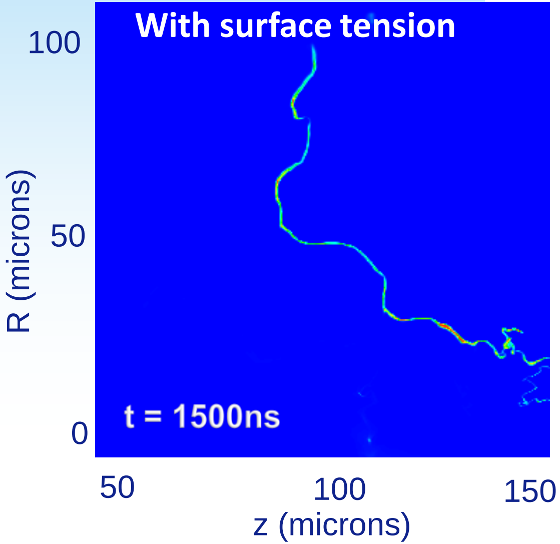
Needed to converge and resolve all the gradients

2. Improved Equation of State, with more resolution and higher accuracy for low temperature Sn



Pressure within a droplet after the laser hits it

3. Inclusion of surface-tension which helps to reduce structure and ripples of the liquid Sn

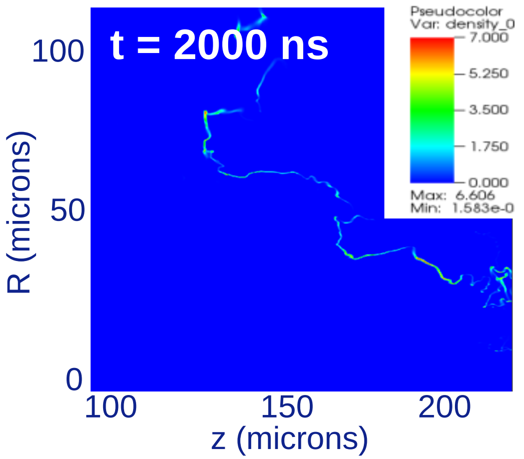


Linear scale density map of the expanded Sn droplet after 1500ns of drift

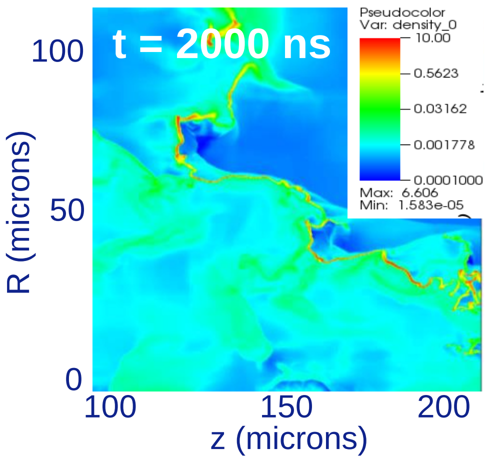
Simulations predict characteristics of the Tin target

Revealing the distribution of density and temperature just before the main laser pulse arrives

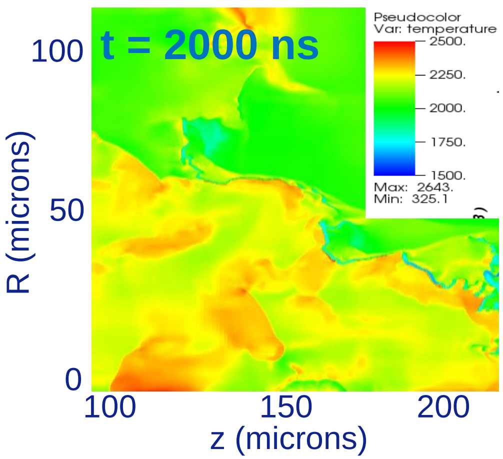
Linear Scale Density Map



Log Scale Density Map

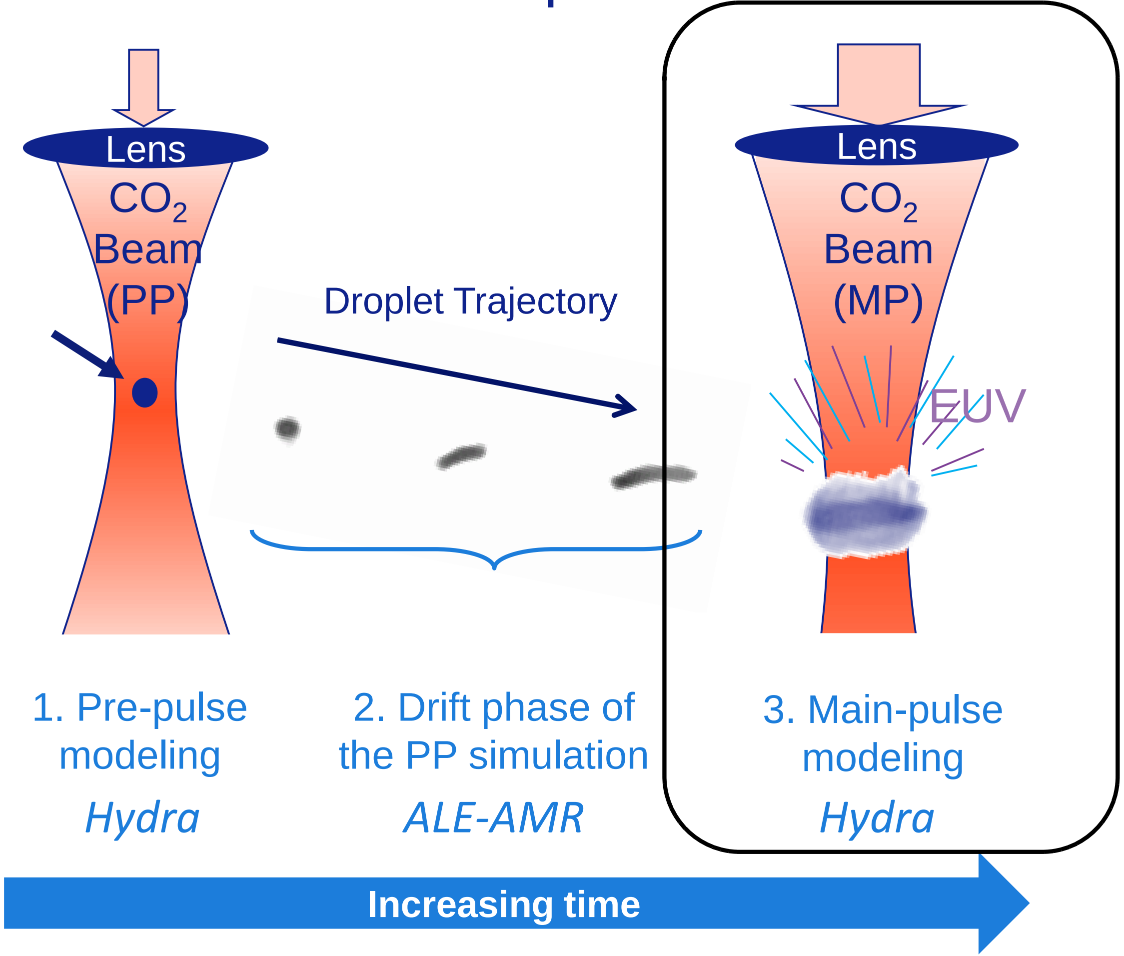


Temperature (K)



Accurately modeling the target formation will impact:
Conversion Efficiency, EUV production, and debris formation.

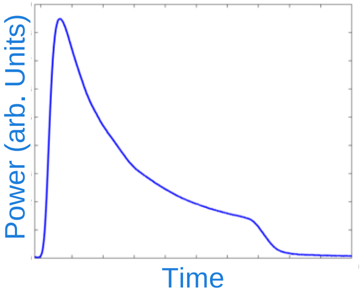
The full problem was broken up into 3 simulation efforts



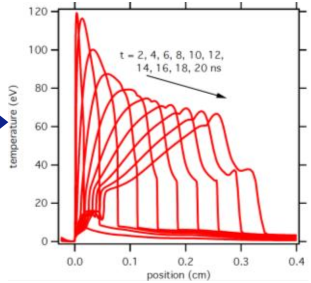
What simulation capabilities have we developed?

Main-pulse modeling using HYDRA

Main-pulse shape

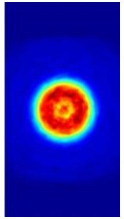


1D:
real pulse shape

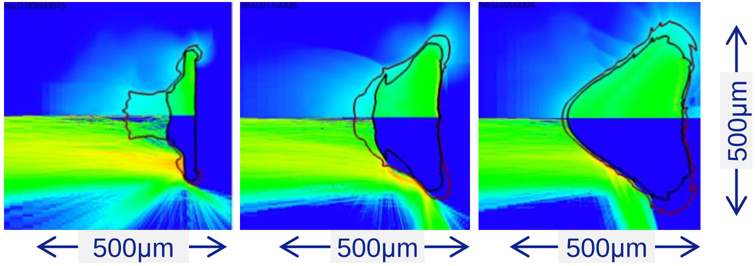


1D simulations are fast and useful for problems that require rapid feedback and less accuracy

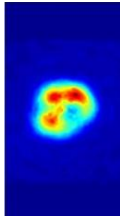
2D:
+ symmeterized beam profile

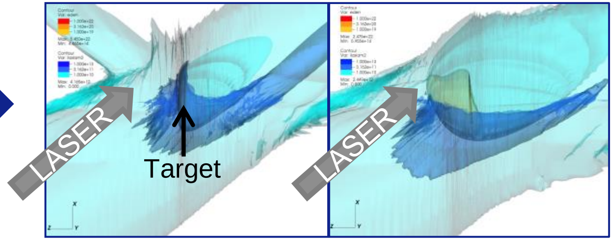


Electron density (top half) with laser light (bottom half)



3D:
+ real asymmetric profile



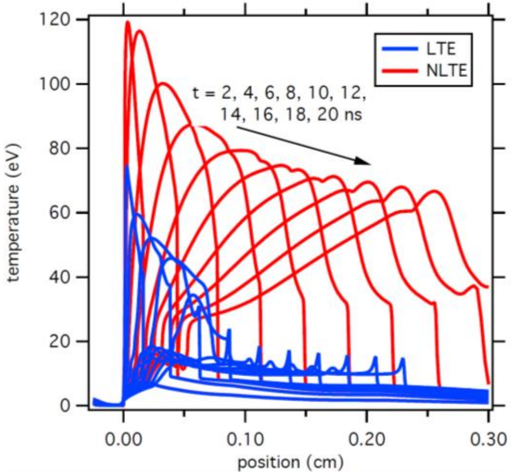


2D and 3D simulations are run for the full duration of the Main pulse. Results include temperature, electron density, spectral emission, etc.

Sn target using a real irradiance distribution

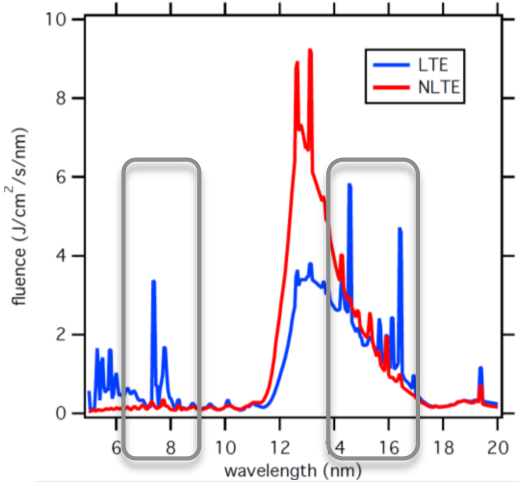
Discovering the physics critical to simulation accuracy

Understanding the assumption of a thermal distribution of excited states



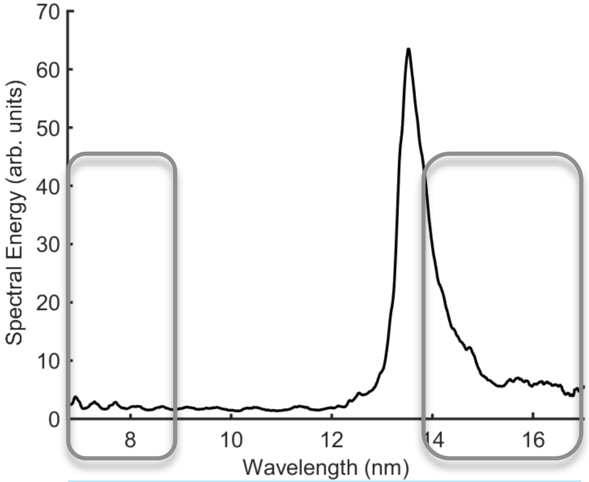
1D calculations confirm that the assumption of a thermal distribution of excited states is not a good approximation.

LTE and NLTE simulations using the same atomic configurations



Calculations that assume LTE lead to emission at higher photon energies.

Measured EUV spectra

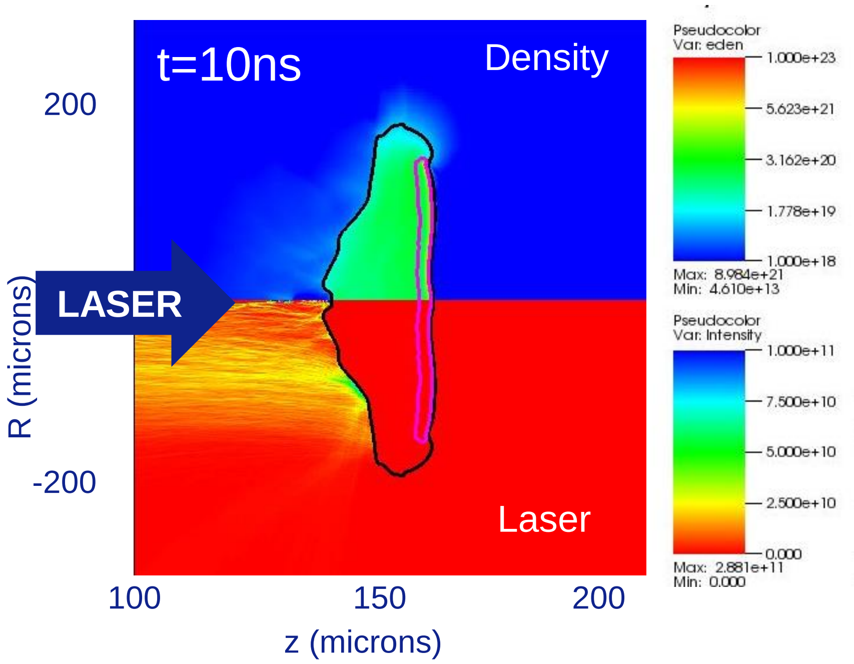


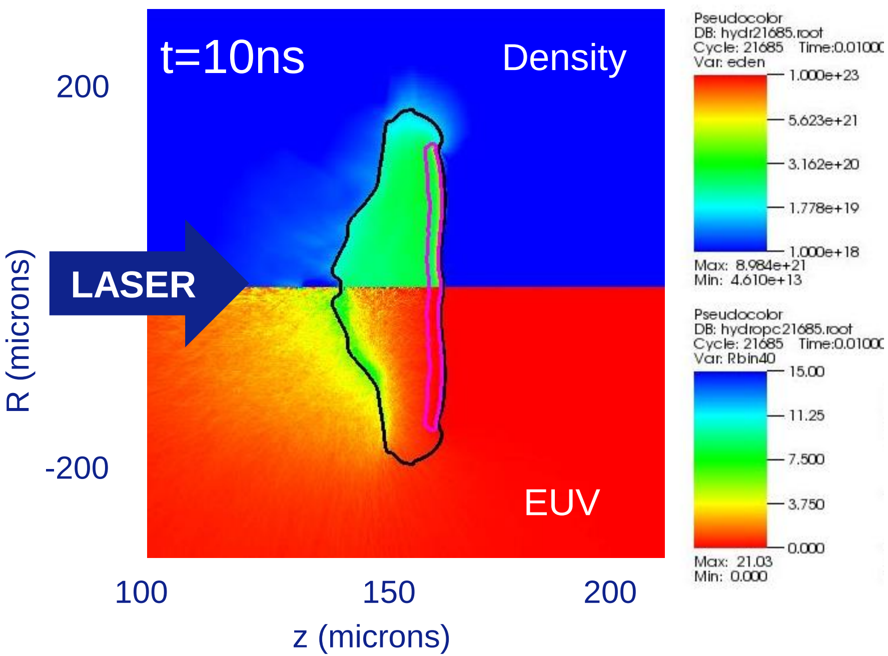
Simulated Spectra were improved using NLTE.

LTE = **L**ocal **T**hermal **E**quilibrium

Understanding EUV emission generation

Visualizing laser interaction and local generation of EUV within a “pre-puffed” Sn droplet



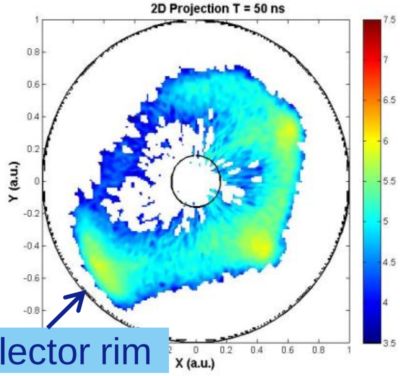


What simulation capabilities have we developed?

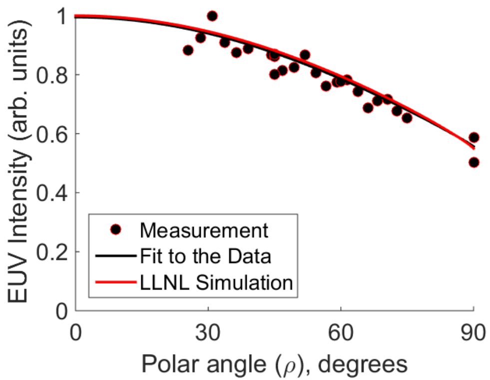
Post-processing of the outputs

The plasma code's outputs were processed to produce synthetic data. The comparison to experiments helps to validate the code and understand it's accuracy.

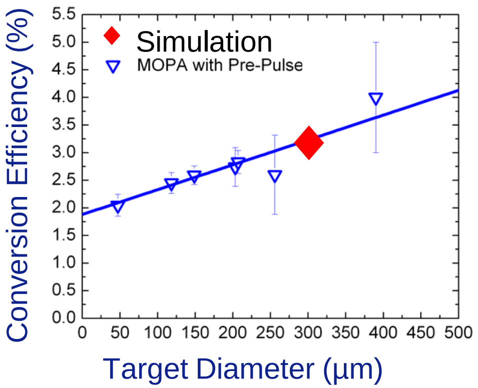
Reflected laser modeling



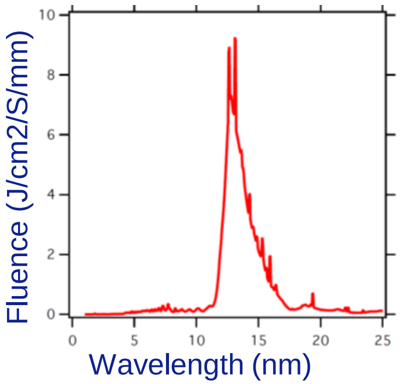
Emission anisotropy



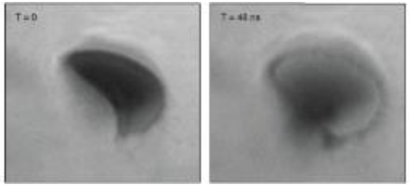
Conversion Efficiency



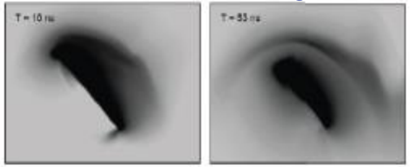
Simulated EUV spectra



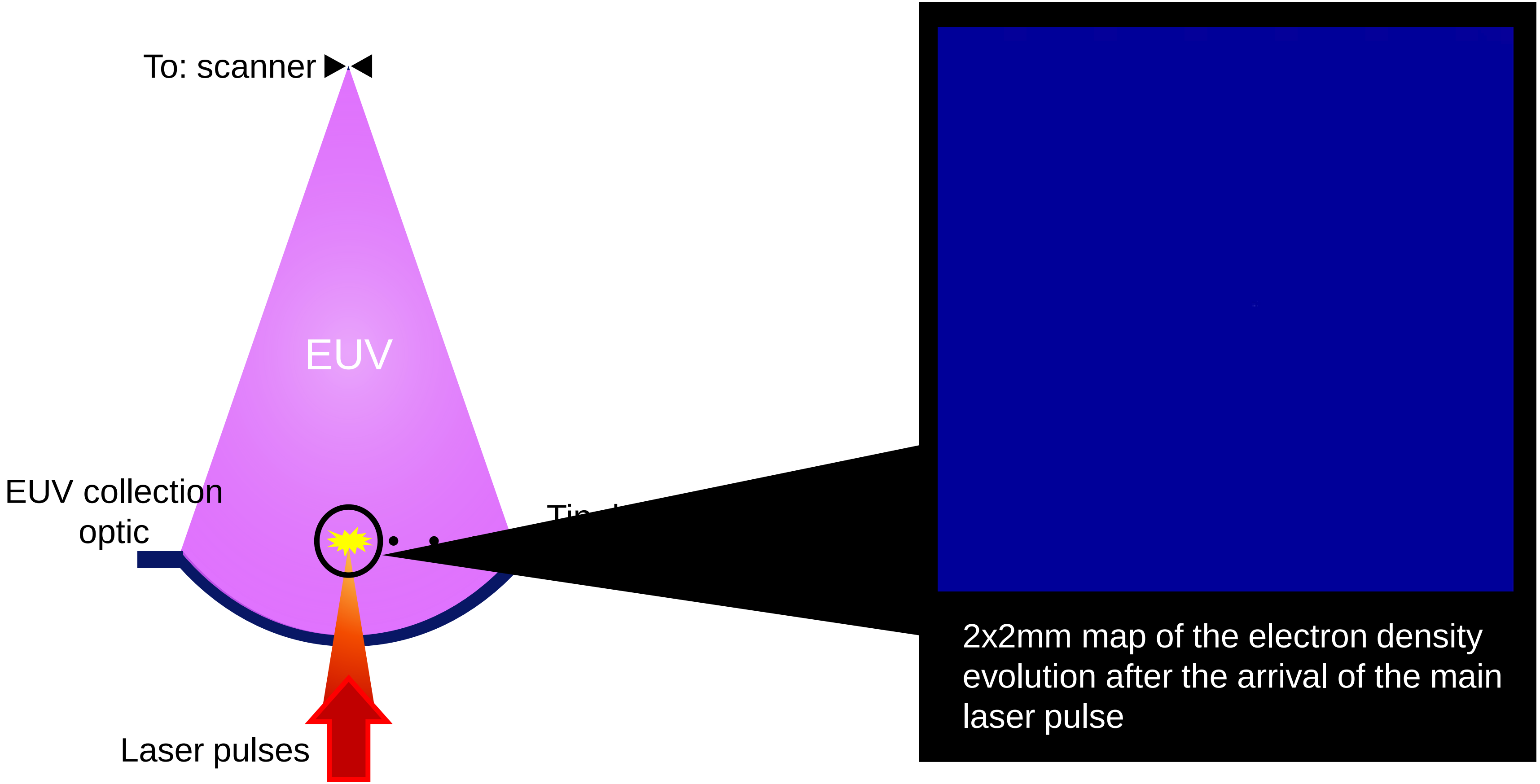
Measured Shadowgrams



Simulated Shadowgrams



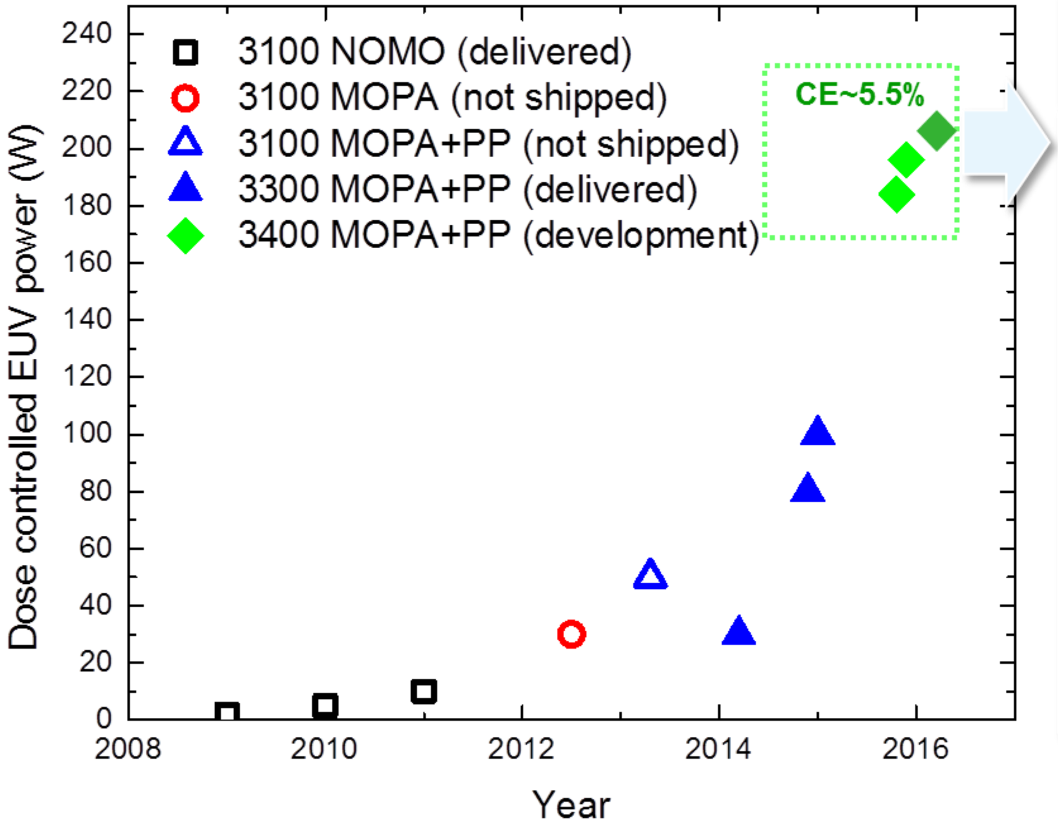
Example of a 2D main pulse simulation



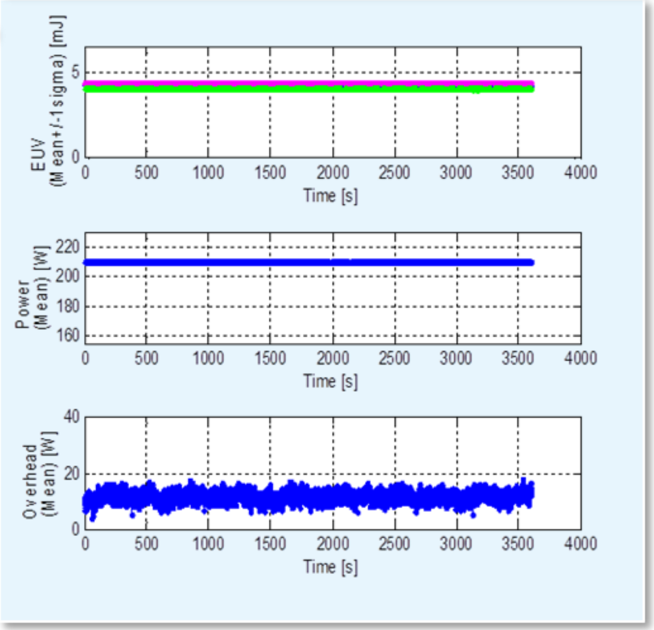
2x2mm map of the electron density evolution after the arrival of the main laser pulse

210 Watt EUV Power

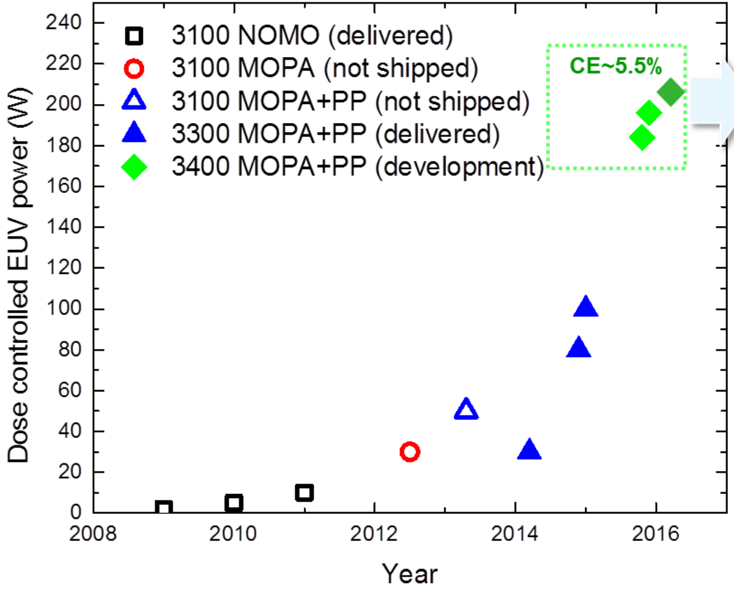
1hr run, >5% CE, meets dose requirements



210W with dose in specifications obtained on development source



Summary:
Connecting with progress in EUV power scaling



- We continue to focus on validating the model and building confidence in simulated outputs.
- After the validation effort, the goal will be to apply the code to EUV power levels not currently accessible in the lab.

Future activities include:

- Refining and speeding up the simulations
- Particle-in-cell simulations to better understand laser-plasma coupling
- Atomic physics modeling
- Studying characteristics of target formation and their impact on CE